4DVAR for Global Atmospheric Numerical Weather Prediction

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LONG-TERM GOALS

The long-term goal of this RTP project is to provide the warfighter with superior battlespace environmental awareness in terms of high fidelity four-dimensional (4D) depiction of the global atmospheric states. This situational awareness is a key aspect of information superiority in the DoD's strategic plan to ensure battlespace dominance in the 21st century. This goal is to be accomplished by providing NOGAPS[1] with best possible initial condition through the use of next generation global atmospheric 4D variational (4DVAR) data assimilation system, NAVDAS-AR[2].

OBJECTIVES

The objective of this project is to construct and transition a 4DVAR global atmospheric data assimilation system for NOGAPS to Fleet Numerical Meteorology and Oceanography Center (FNMOC). This system, NAVDAS-AR, represents the first operational, weak constraint, 4DVAR atmospheric data assimilation system in the world. In this context, "weak constraint" means that the atmospheric forecast model is not considered a "perfect" model, but rather is assumed to have errors. This enables the most optimal solution. NAVDAS-AR will provide high fidelity, dynamically consistent analyses for NWP model initialization and for warfighter support, and will be capable of efficiently handling large numbers of observations that may be irregularly distributed in space and time, and/or indirectly related to the model state variables (e.g., satellite radiances or wind vectors).

APPROACH

Our approach is to build on the prototype of NAVDAS-AR (Xu et al 2005, and Rosmond and Xu 2006) that has been developed and successfully applied to the global 4DVAR data assimilation application using the NOGAPS prediction model as a dynamic constraint. This project, which is a follow-up to a NRL ongoing in-house 6.2 data assimilation project, will expand this prototype to a next-generation operational global atmospheric data assimilation system. We will leverage the existing NAVDAS and NOGAPS infrastructures to provide the pre- and post- analysis processes. The system will be thoroughly tested using scientific studies, and comprehensive data assimilation and forecast experiments. Although the goals are ambitious, they are realistic because the theoretical basis for the project is already in place owing to great progress made in our 6.1 and 6.2 in-house data assimilation projects on variational data assimilation.

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[1] NOGAPS: Navy Operational Global Atmospheric Prediction System
[2] NAVDAS-AR: NRL Atmospheric Data Assimilation System – Accelerated Representer

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14. ABSTRACT
The long-term goal of this RTP project is to provide the warfighter with superior battlespace environmental awareness in terms of high fidelity four-dimensional (4D) depiction of the global atmospheric states. This situational awareness is a key aspect of information superiority in the DoD?s strategic plan to ensure battlespace dominance in the 21st century. This goal is to be accomplished by providing NOGAPS1 with best possible initial condition through the use of next generation global atmospheric 4D variational (4DVAR) data assimilation system, NAVDAS-AR2.

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WORK COMPLETED

The following is a list of work completed related to this project during FY07.

1. Developed and tested a new highly parallel 2D domain decomposition algorithm that greatly improved the runtime speed of the NAVDAS-AR.

2. Developed the adjoint system of NAVDAS-AR, which is capable of examining the temporal aspect of the observation sensitivities.

3. Implemented and tested a new minimization algorithm, Flexible Conjugate Gradient (FCG), to replace the current standard Conjugate Gradient (CG).

4. Implemented and tested a convolution algorithm, which accounts for the impact of model error in 4DVAR algorithm such as NAVDAS-AR, to the Burger's equation.

5. Completed the development and test of AMSU-A radiance assimilation and the associated bias correction. We also started to assimilate temperature and humidity information from other microwave and infrared sensors.

6. Conducted extensive data assimilation experiments for July-Aug 2005 and Feb-March 2006.

7. Started to run NAVDAS-AR in real time pre-operational mode on FNMOC's new Linux Cluster system – A2 and the IBM – AMS5.

These FY07 accomplishments are critical for the comprehensive data assimilation tests under real time operational environment and the AMP transition of NAVDAS-AR to FNMOC planned for FY08.

RESULTS

The following results represent some highlights of the several significant accomplishments of this project during FY07.

A new parallel computation algorithm for NAVDAS-AR

One of the important milestones set for FY07 was to substantially improve the actual runtime of NAVDAS-AR. A new 2D domain decomposition parallel algorithm has been developed for NAVDAS-AR by Dr. Rosmond. The original NAVDAS-AR code was written for only a 1D latitude band decomposition, which limited the maximum processor number to 60 for the current T79 inner loop resolution. While presently that is not a limitation, since we always run with 40 processors on the FNMOC's IBM-AMS5, future systems may allow much larger processor numbers. If we want to increase the resolution of the inner loop, and also reduce AR runtime, we need the ability to run with substantially more processors if available. With 2D decomposition and T79 we can run with up to 450 processors, and for a T159 inner loop (this is what ECMWF runs), up to 1800 processors.

An added benefit of the 2D decomposition is that there is a noticeable decrease in runtime for some of the now allowable IPROC/JPROC combinations. Attached is a histogram plot of AR runtime for several of these combinations. The 1x40 far left bar is the current 1D decomposition (IPROC=1, JPROC=40). The 4x10 and 5x8 times are about 12% less that the 1x40. Interestingly, this is contrary to our experience with the NOGAPS forecast model, which has always had 2D decomposition. Any IPROC=1, JPROC=xx has almost always been the best choice for the model. Apparently ANAVDAS-AR benefits from a more even distribution of processors due to better load balance in observation space and more efficient MPI when going between observation volume space and grid point lat-lon space.

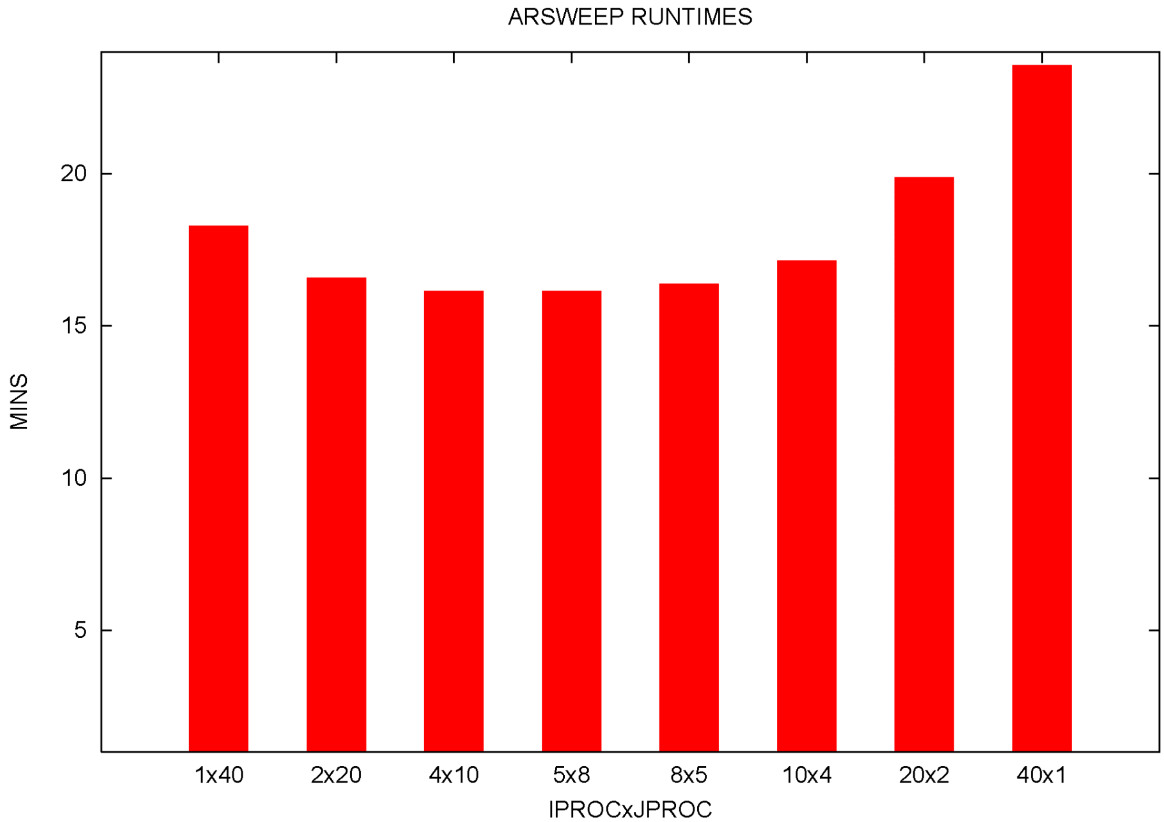

Figure 1: The new 2D domain decomposition parallel computation algorithm not only allows NAVDAS-AR to use more processors, but also produces a noticeable decrease in runtime for some of the now allowable IPROC/JPROC combinations. [Graphic shows the reduction of runtime for NAVDAS-AR using the new parallel algorithm.]

The Adjoint system of NAVDAS-AR

The adjoint of NRL Atmospheric Variational Data Assimilation System (NAVDAS), an observation-space 3D-Var, has been developed at NRL in Monterey, CA, USA. The adjoint of NAVDAS has proven to be very useful in estimating the impact of observations on the short-range forecast error in NWP in the past several years. Due to the limitations of 3D-VAR, however, the NAVDAS adjoint does not properly account for the temporal distribution of the observations. To address the temporal aspects of observation impact, we are currently developing and testing the adjoint of NAVDAS-AR (accelerated representer), an observation-space 4D-Var, at NRL-Monterey. The new capability of estimating the temporal aspect of observation impact is likely to become increasingly important in the future as asynoptic observations become much more dominant. In this presentation, we first give a brief description of the formulation and basic design. Figure 2 shows the results of assessing the observation impact using the adjoint system of NAVDAS-AR. The observation impact is sorted by the observation types. More details are given by Xu et al. (2006 and 2007).

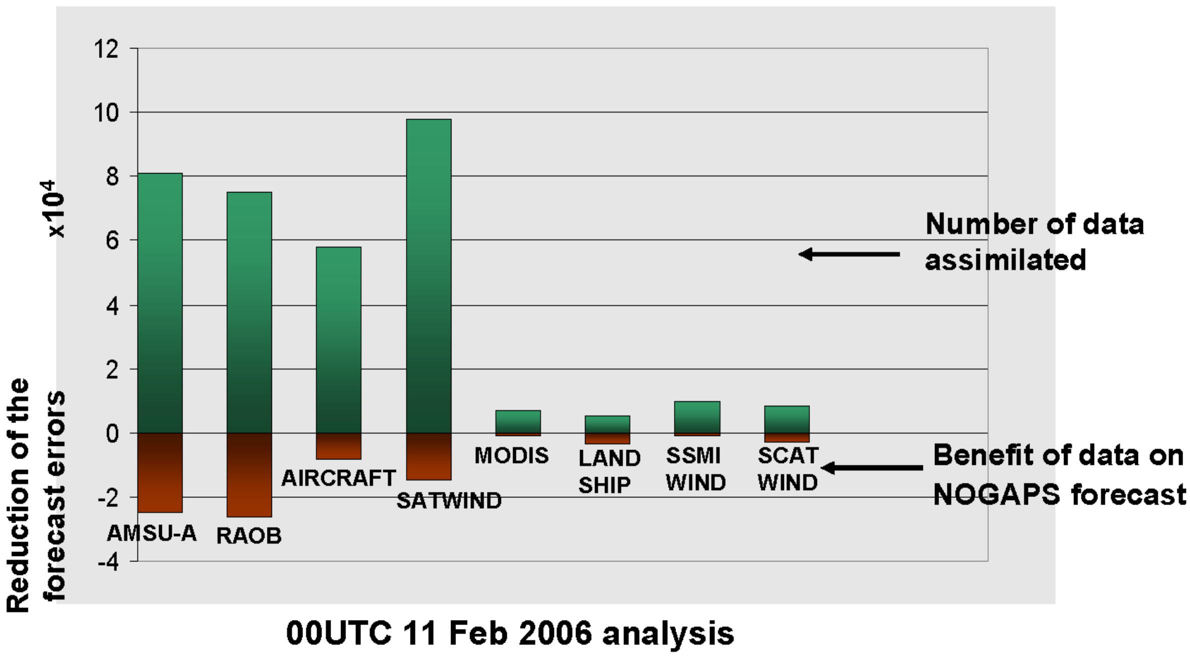

Figure 2: The ability of the adjoint of NAVDAS-AR to assess and monitor the impact of observations on NOGAPS forecast. [Graphic shows RAOB is the most beneficial observation type that improves the NOGAPS forecast, followed by AMSU-A, SATWIND, AIRCRAFT, etc.]

A new minimization algorithm (FCG) for NAVDAS-AR

Conjugate gradient algorithm has been widely used in find solutions for high-dimension linear equations. However, the convergence rate of standard conjugate gradient algorithm decreases after certain number of iterations due to the inability of the CG algorithm to keep the current and previous search directions being orthogonal with each other. This issue is caused by the computational errors caused by the finite accuracy of computers. The new FCG algorithm avoids the pitfall of the CG by reorthogonal the search directions such that the orthogonality of the search directions is always preserved. As we can see from Fig 3, the FCG reaches the so called “super linear convergence.

An efficient weak constraint algorithm to be used in NAVDAS-AR

Strong constraint (perfect model assumption) 4D-Var algorithms are increasingly used for synoptic and global scales atmospheric data assimilation at operational numerical weather prediction centers around the world. The data assimilation windows currently range from 6 hours to 12 hours at different centers. It is preferable to have as many independent observations as possible in each data assimilation window under the variational framework. Longer data assimilation windows generally increase the information content from the observations, but also make the perfect model assumption more improper. It is clear that weak constraint (imperfect model assumption) 4D-Var algorithms will be required to properly combine the background forecast with high resolution observations in longer data assimilation windows in the not too distant future.

Despite the weak constraint formulation, the current NAVDAS-AR implementation uses the perfect model assumption. We proposed to treat the impact of the model errors as a residue term resulted from a four-dimensional matrix/vector multiplication of the model error covariance with the adjoint field in the right hand side of the tangent linear model. The calculation of the residue term is generally very computationally intensive. However, it can be obtained accurately and efficiently when some special choices are made for the model error covariances using a special approach (Chua and Bennett, 2001). The steps involved in this approach are demonstrated through application to the Burgers' equation (Xu et al. 2007).

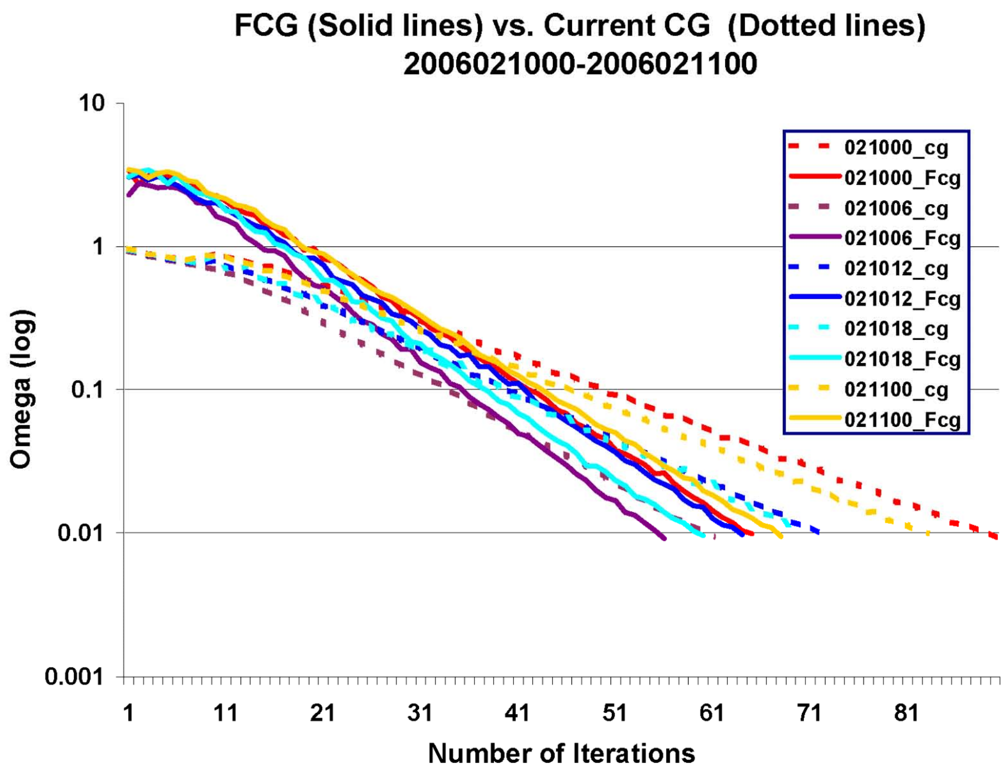

Figure 3: The number of iterations required for NAVDAS-AR to converge to the specified criteria (Omega(log)=0.01). Same color represents one date-time-group of data assimilation cycle with solid lines for FCG and dotted lines for CG. [Graphic shows FCG consistently requires less number of iterations (less computational cost) to converge than the CG does.]

IMPACT/APPLICATIONS

The current operational data assimilation system at FNMOC, NAVDAS, is based on a three-dimensional variational (3DVAR) algorithm and is cast in observation space. The 3DVAR algorithm is widely used in intermittent cycling data assimilation for the analysis of global and synoptic scales around the world. It can handle relatively slowly evolving flows and observation platforms that sample heterogeneously in space, but assume that the observations are taken at the analysis time. However, highly intermittent flows that are not governed by simple balance relationships, and observation systems that sample irregularly in time, or with high temporal frequency, are not well accommodated within an intermittent 3DVAR framework but can be accommodated by a 4D data assimilation system. Furthermore, an intermittent 3DVAR algorithm produces a “snapshot” of the atmosphere at the center of the typical 6-hour observation time window, automatically making the resulting atmospheric analysis at least 3 hours old.

With NAVDAS-AR, a continuous picture of the atmosphere over the observation time window is produced, providing an atmospheric analysis at the end of the time window that is current rather than 3 hours old. Although NAVDAS has been quite successful, a 4D data assimilation system is a necessity to significantly improve not only the accuracy of the common operational picture required by the warfighter but also the timeliness of providing this more accurate picture to the warfighter. The advanced 4DVAR data assimilation algorithm, NAVDAS-AR, will provide the basis for this system. Only through 4DVAR algorithms can we truly exploit many of the observations from current and future observing systems. This is especially important for remotely sensed observations that are nonlinearly and indirectly related to the model state variables (e.g., satellite radiances and GPS radio occultation measurements). In addition, the computational efficiency of NAVDAS-AR with respect to the number of observations makes it more efficient than the NAVDAS 3DVAR system in handling the monumental increase in the volume of satellite data expected over the next decade.

TRANSITIONS

Improved algorithms for NAVDAS-AR have been transitioned to the 6.4 component of this project, and will ultimately be transitioned to FNMOC in FY08 as the Navy’s next generation operational global atmospheric data assimilation system.

RELATED PROJECTS

Some of the technologies developed for this project will be used immediately to improve the current operational data assimilation system and the observational impact in other NRL projects. The NAVDAS-AR has been recognized as a viable framework for various data assimilation applications, such as the ocean data assimilation system project (NRL base).

PUBLICATIONS

1. Xu, L., T. Rosmond, J. Goerss, and B. Chua, 2007: Toward an operational weak constraint 4D-Var system: application of the Burgers’ equation. *Meteorol. Z.* (in press)

2. Xu, L., R. Langland, N. Baker, and T. Rosmond, 2007: Development of the NRL 4D-Var data assimilation adjoint system. (To be submitted to *Tellus*)

3. Xu, L., T. Rosmond, N. Baker, and J. Goerss, 2007: An Advanced Framework for Battlespace Environment Data Assimilation. 2006 NRL review.

PRESENTATIONS

1. Rosmond, T., L. Xu, N. Baker, B. Campbell, C. Blankenship, J. Goerss, B. Ruston, and P. Pauley, 2006: Direct radiance assimilation with NAVDAS-AR. The Seventh International Workshop on Adjoint Applications in Dynamic Meteorology, Obergurgl, Austria, 8-13 October 2006.

2. Xu, L., R. Langland, N. Baker and T. Rosmond, 2006: Development and Testing of NAVDAS-AR. The Seventh International Workshop on Adjoint Applications in Dynamic Meteorology, Obergurgl, Austria, 8-13 October 2006.

3. Xu, L., T. Rosmond, J. Goerss, and B. Chua, 2007: Toward a weak constraint 4D-Var system: application of the Burgers equation. The 18th Conference on Numerical Weather Prediction 25 June - 29 June 2007, Park City, UT.

4. Xu, L. and B. Chua, 2007: Preconditioning NAVDAS-AR using IOM preconditioners. Yoshi K. Sasaki Symposium on Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications AOGS 2007, 29 July – 3 August 2007, Bangkok.